Enhanced DM Constraints via Neutrino Direction Reconstruction

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IHEP

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Gravitational Evidence for Dark Matter

➢ The evidence for the existence of DM spans observations across diverse scales

- Rotation Curve
- Collisions of Galaxy Clusters
- Large Structure Formation
- Cosmic Microwave Background

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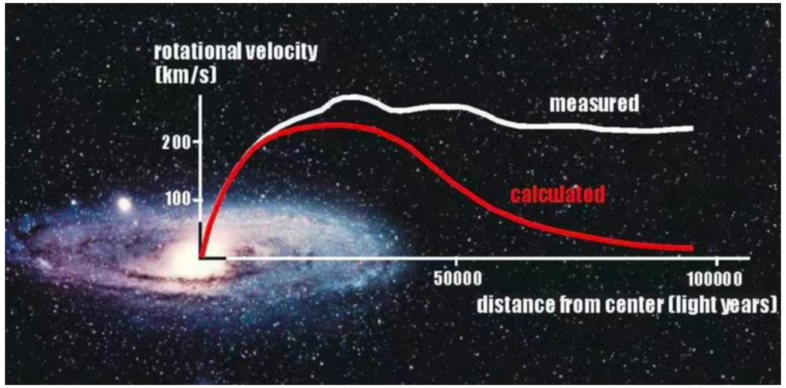
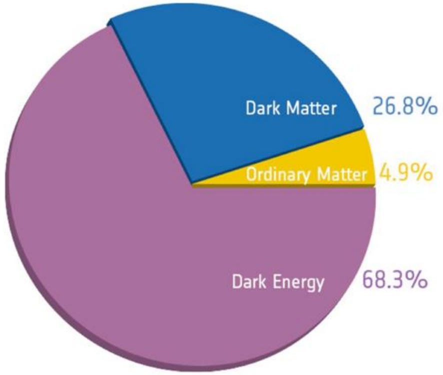
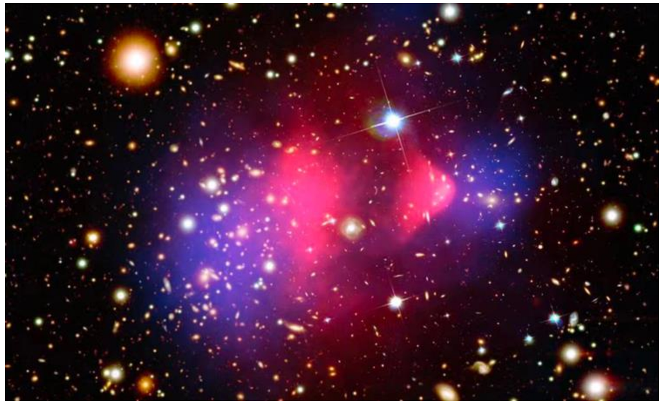
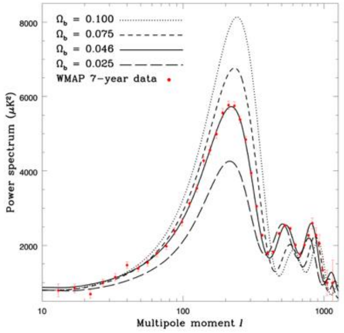








Dark Matter Detection

- Direct Detection

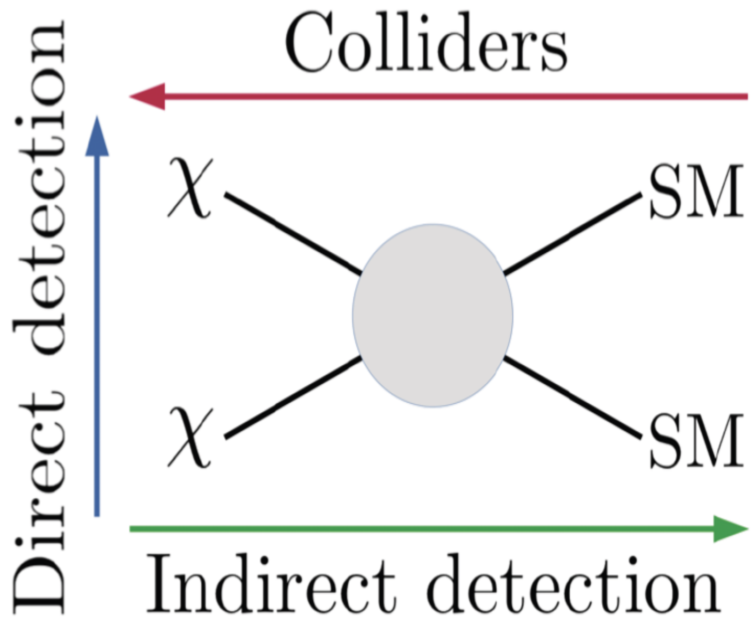
    Nuclear recoil energy

- Collider search

    Missing transverse energy

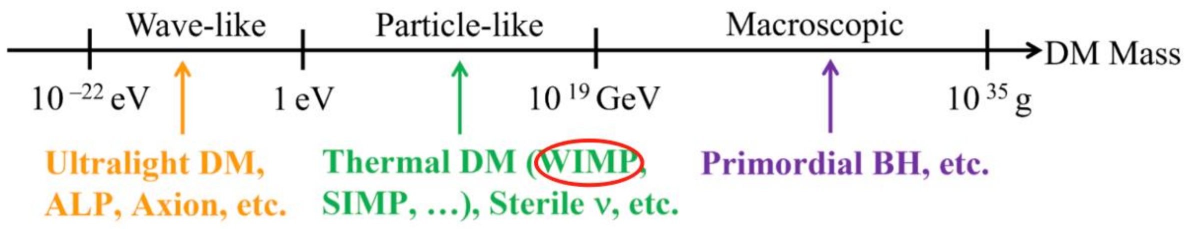
- Indirect detection/Astrophysical search

    Observable Standard Model particles, similar to processes in the early Universe

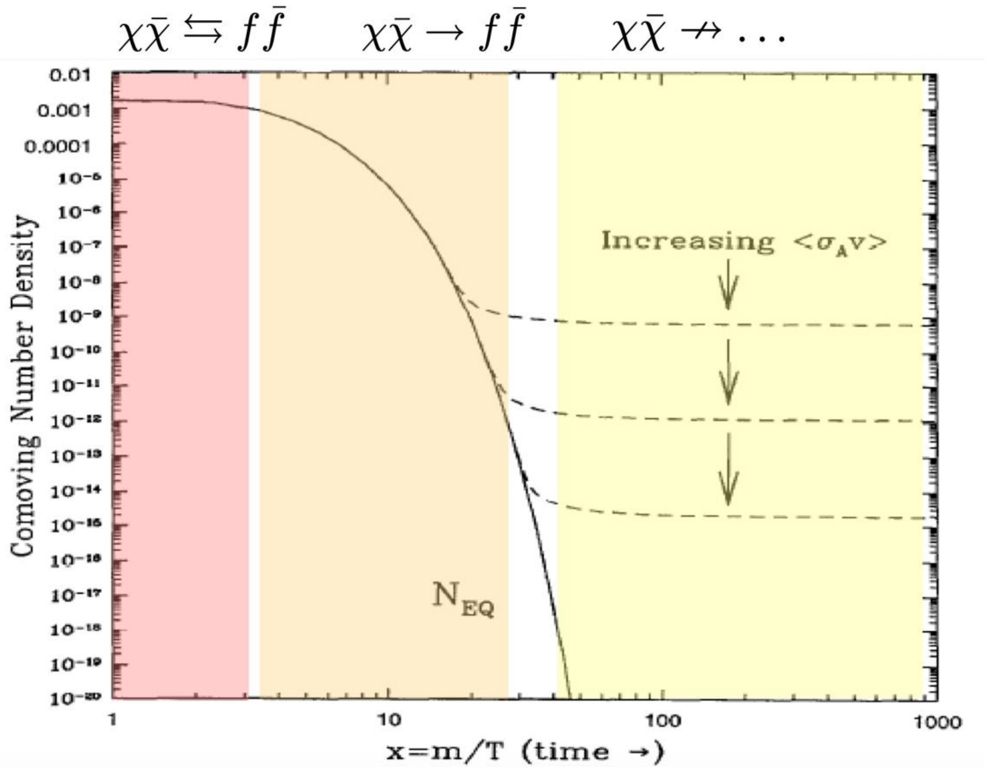


A. Arbey & F. Mahmoudi, 2021

Theoretical Motivation



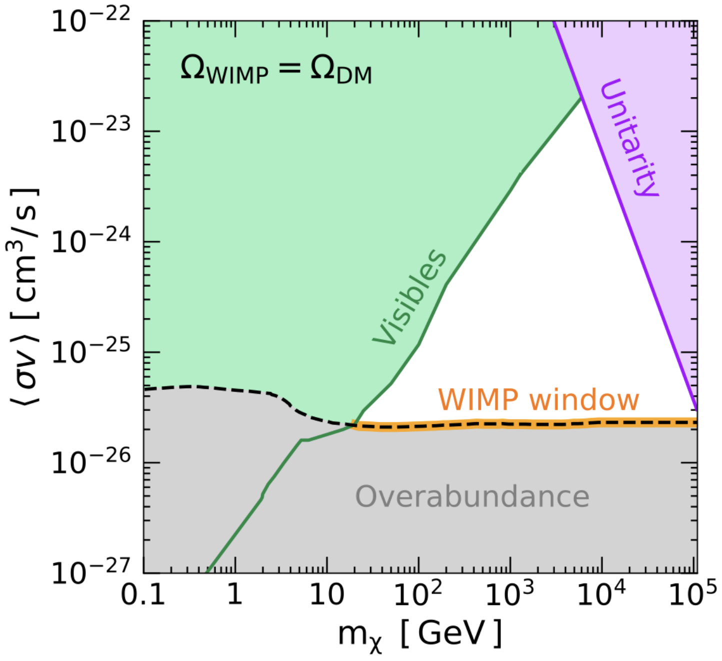
- DM abundance can be naturally obtained by freeze-out of weak-scale DM annihilations
- In thermally equilibrium at high temperature
- Decouple as the Universe expanded and cooled $\Gamma_{\rm ann} \lesssim H$
- Relic abundance depends on cross section, the weaker, the more abundant



E. W. Kolb and M.S. Turner, The Early Universe

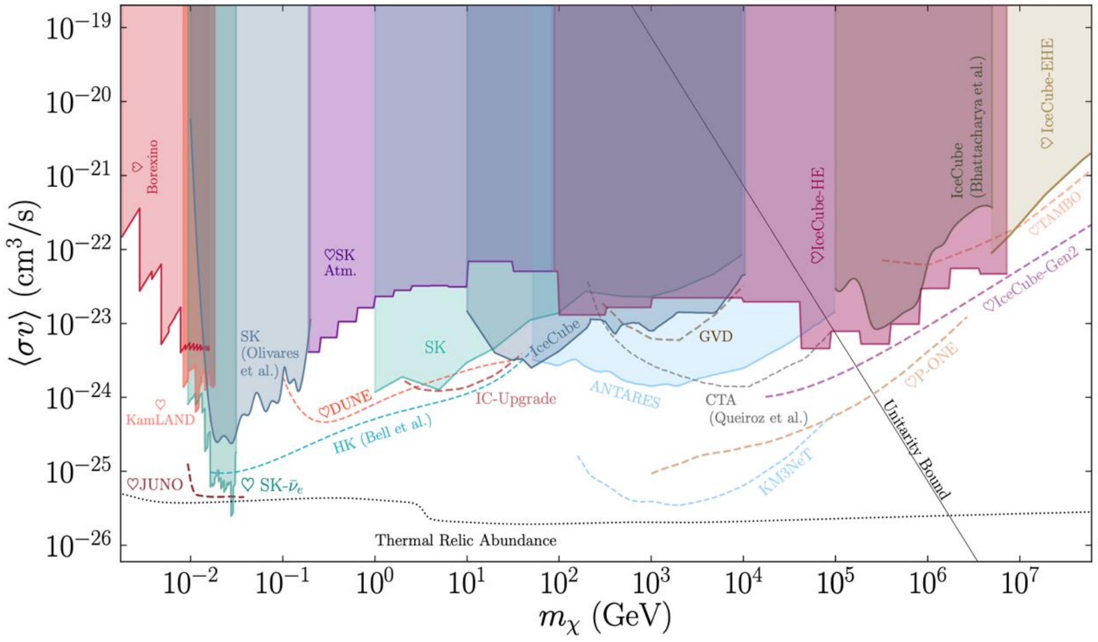
DM Annihilation

s-wave with 2 → 2 annihilation to visible final states



RK Leane et al., 2018

Only neutrino channel (bottleneck)



CA Argüelles et al., 2019

Even for the simplest WIMP scenario, the total annihilation cross section is not fully constrained

J Factor in DM Annihilation

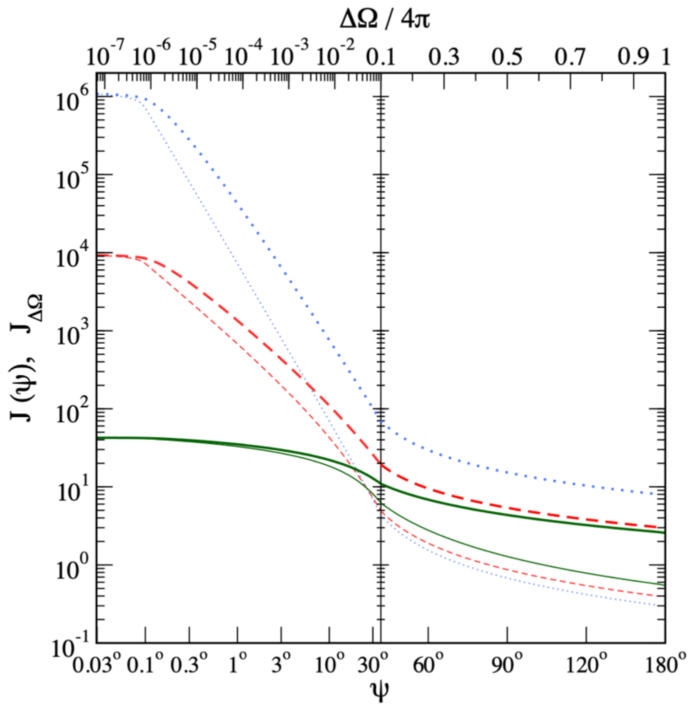
The average intensity of DM annihilation products

$$\frac{d\Phi_{\Delta\Omega}}{dE} = \frac{\langle\sigma_A v\rangle}{2} \mathcal{J}_{\Delta\Omega} \frac{R_{sc}\rho_{sc}^2}{4\pi m_\chi^2} \frac{dN}{dE}$$

Directional information can increase the average J Factor

$$\mathcal{J}_{\Delta\Omega} = \frac{1}{\Delta\Omega} \int_{\cos\psi}^{1} \mathcal{J}(\psi')\, 2\pi\, d(\cos\psi')$$

$$\Delta\Omega = 2\pi(1 - \cos\psi)$$



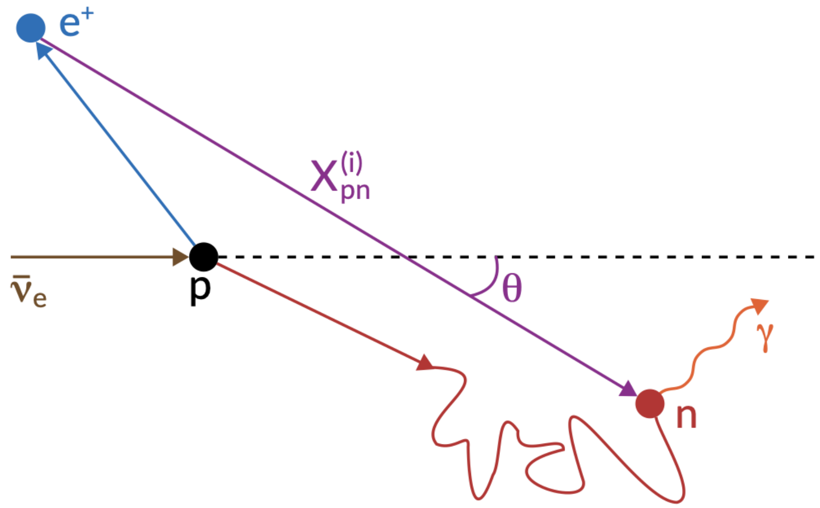
Moore, NFW and Kravtsov in order of dotted, dashed and solid lines

Hasan Yuksel et al., 2007

Inverse Beta Decay Directionality

- Liquid Scintillator Detector

The prompt signal from positron annihilation in IBD is followed by a delayed signal from neutron capture



Mainak Mukhopadhyay et al., 2020

Hui-Ling Li et al., 2020

V. Fischer et al., 2015

M. Apollonio et al., 2000

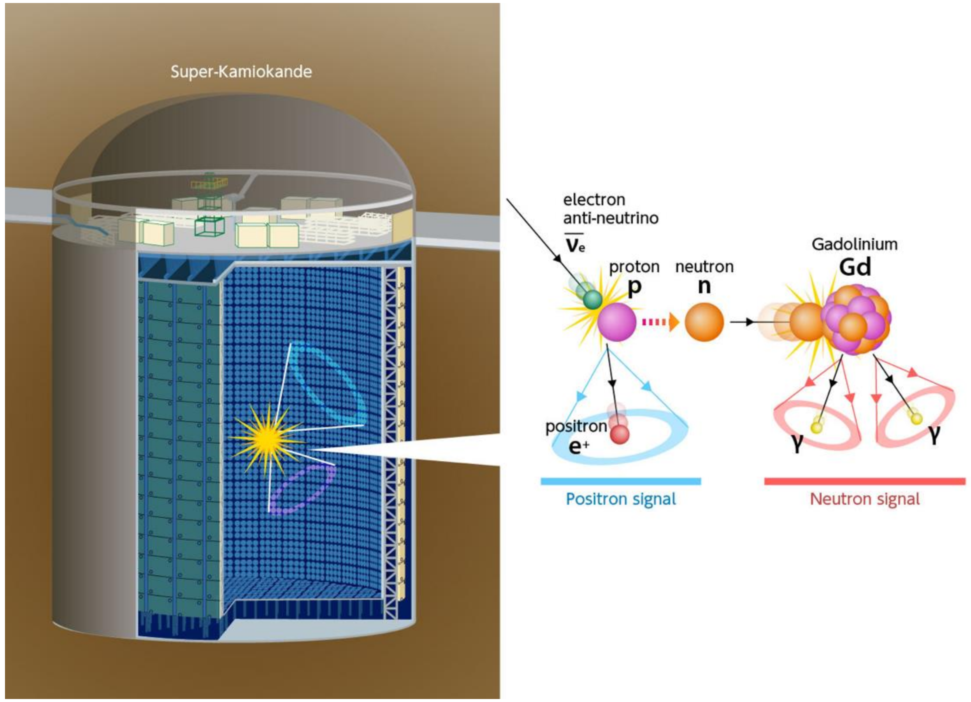
P. Vogel & John F. Beacom, 1999

Inverse Beta Decay Directionality

- Water Cherenkov Detectors

No directionality before because positrons direction is mostly isotropic

Now GADZOOKS make it possible

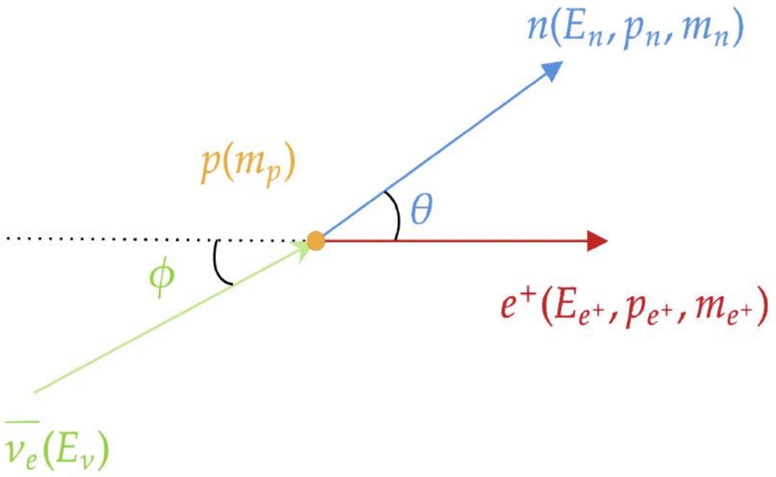


● ~49,000 barns for Gd (30μs for capture with ~8MeV gamma cascade)
● 0.3 barns for H (200μs for capture with a 2.2MeV gamma ray)

Kinematics of Inverse Beta Decay

$$\begin{bmatrix} E_\nu \\ E_\nu \cos\phi \\ E_\nu \sin\phi \\ 0 \end{bmatrix} + \begin{bmatrix} m_{\mathrm{p}} \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} E_{\mathrm{n}} \\ p_{\mathrm{n}} \cos\theta \\ p_{\mathrm{n}} \sin\theta \\ 0 \end{bmatrix} + \begin{bmatrix} E_e \\ p_e \\ 0 \\ 0 \end{bmatrix}$$

$$\bar{\nu}_e + p \rightarrow e^+ + n$$



Five equations (2D) :

$$\begin{cases} E_\nu + m_{\mathrm{p}} &= E_{\mathrm{n}} + E_e \\ E_\nu \cos\phi &= p_{\mathrm{n}} \cos\theta + p_e \\ E_\nu \sin\phi &= p_{\mathrm{n}} \sin\theta \\ m_e^2 &= E_e^2 - p_e^2 \\ m_{\mathrm{n}}^2 &= E_{\mathrm{n}}^2 - p_{\mathrm{n}}^2 \end{cases}$$

Seven parameters :

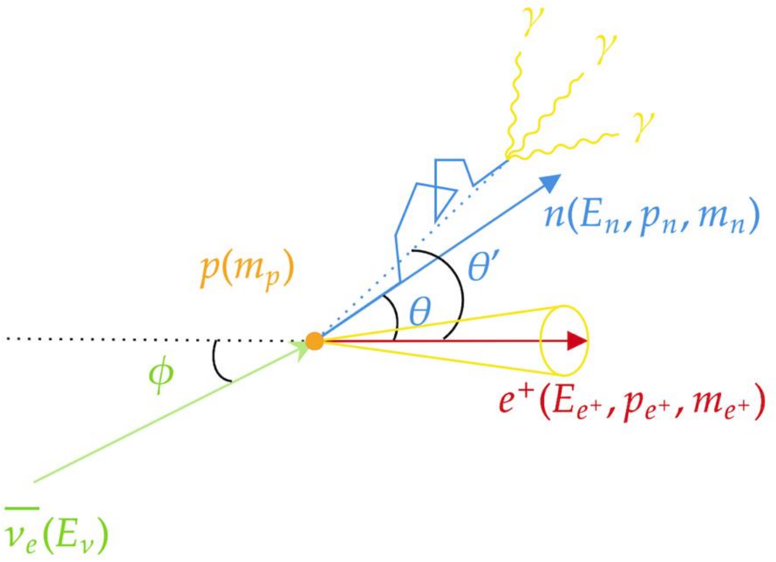
the momenta p_e, p_{n}, particle energies E_ν, E_e, E_{n}, and the two angles θ and ϕ

Kinematics of Inverse Beta Decay

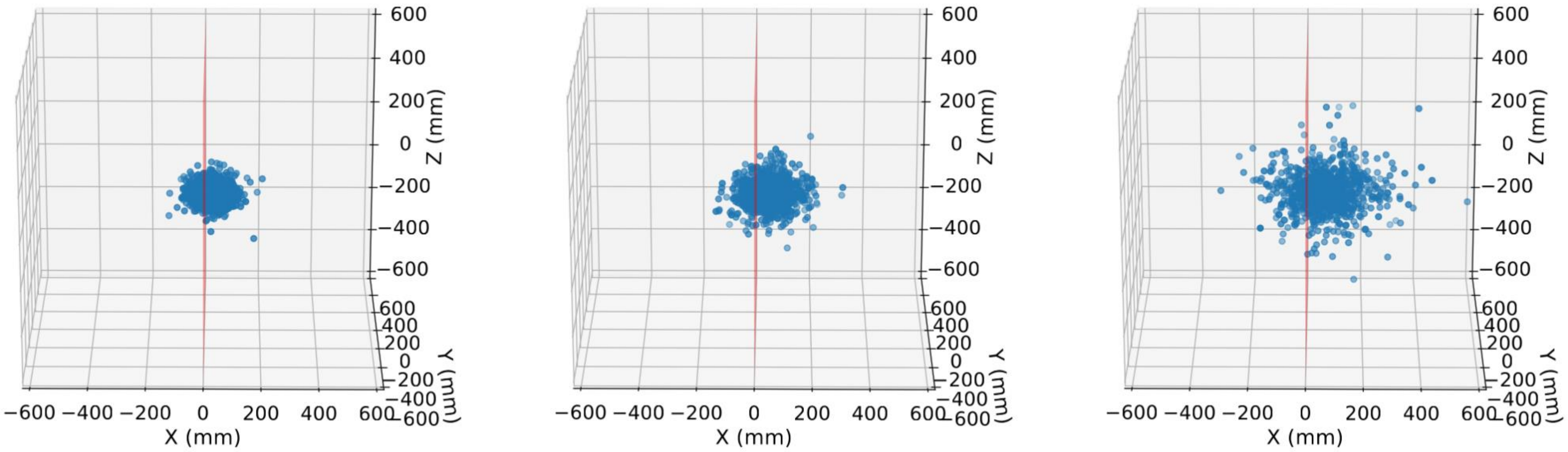
5 equations + 7 unknows

need 2 parameters from measurements

- Positron energy can be measured from Cherenkov light
- Just need one more parameter: Neutron angle or neutron momentum



Geant4 Simulation for Neutron Capture Positions

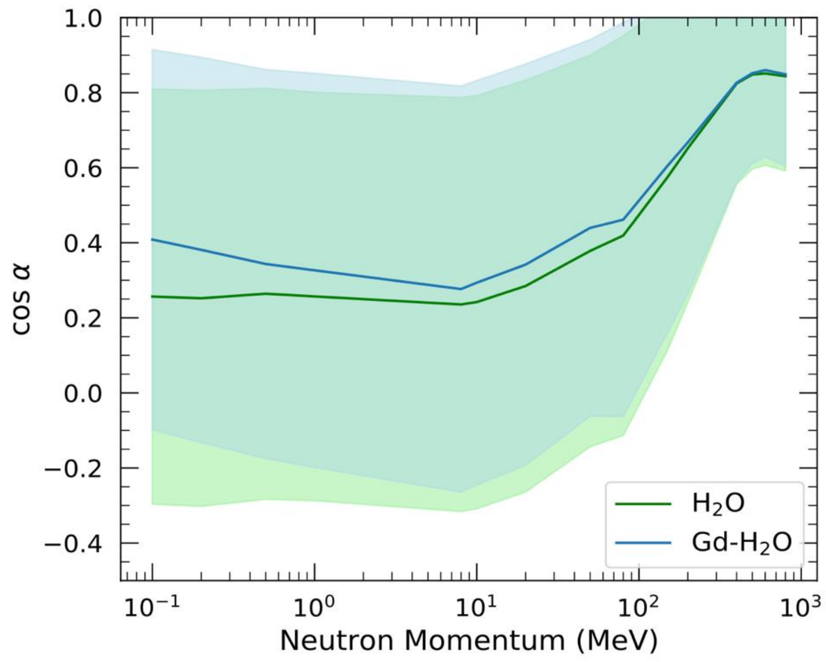


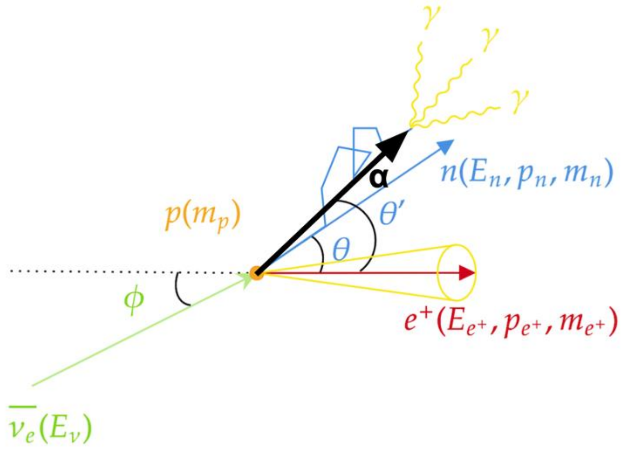
Neutron capture positions in 0.1% Gd-loaded water 20 MeV (left), 50 MeV (middle) and 80 MeV (right) neutron momenta are emitted along the x-axis

Some neutron directionality remains even after diffusion (3D)

The asymmetry is larger for larger neutron momentum

Direction Information in Geant4 Simulation



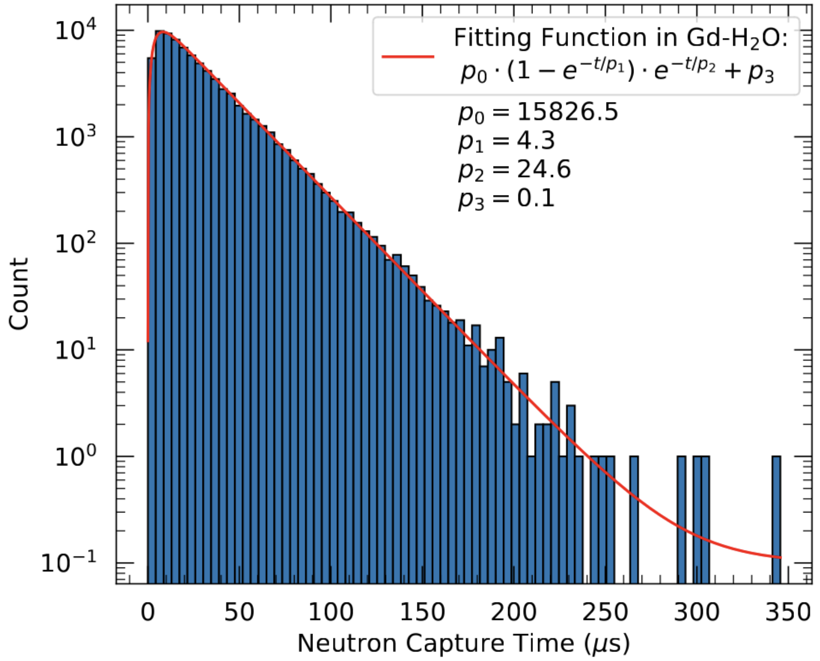


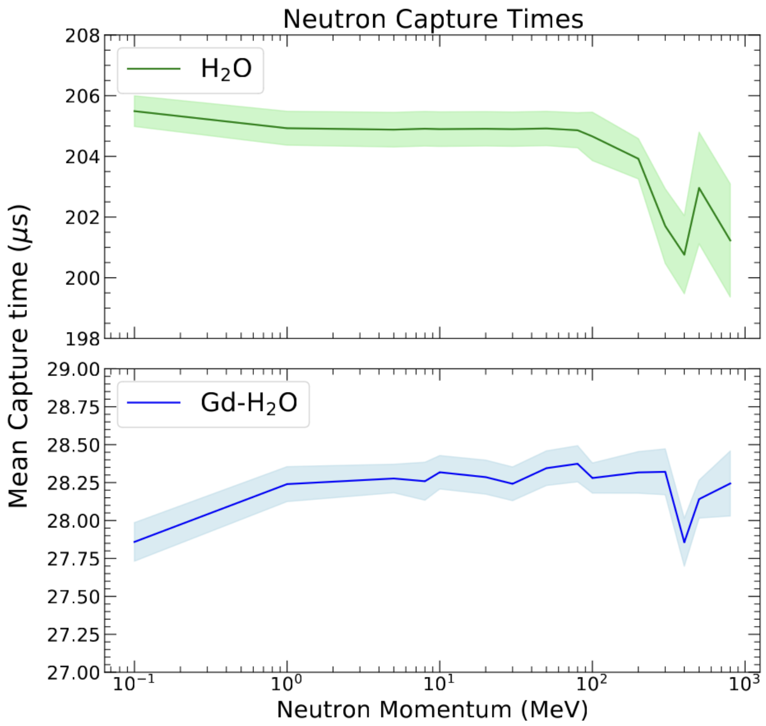
A neutron vector constructed by connecting the original point and the capture position point.

The angle **α** is the angle between the neutron vector and the original direction

Higher momentum neutrons preserve more directional information

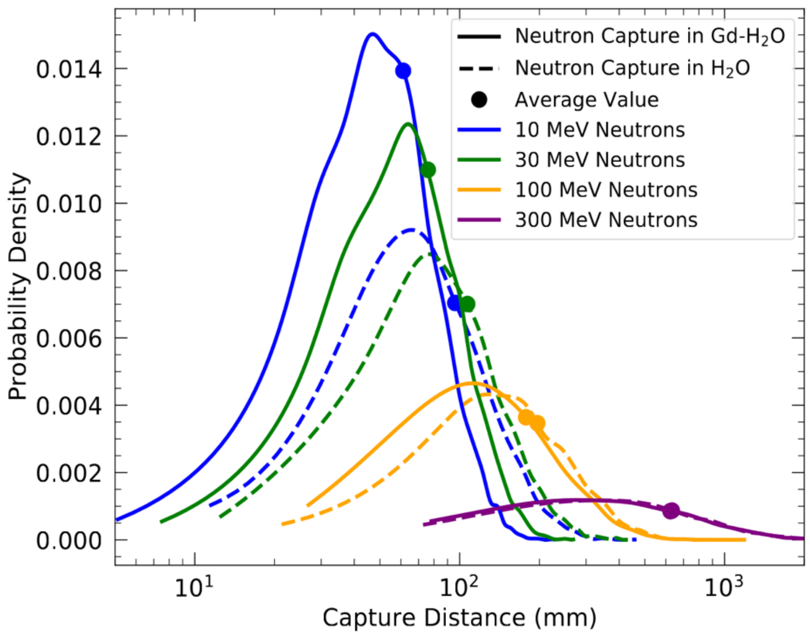
Time Information in Geant4 Simulation

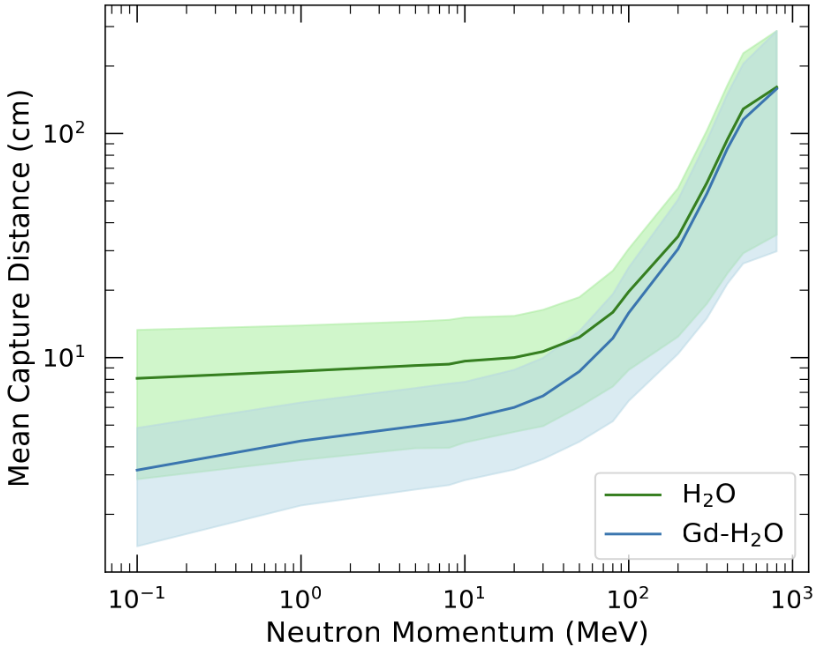




The neutron capture time does not have a strong correlation with the neutron momentum

Distance Information in Geant4 Simulation





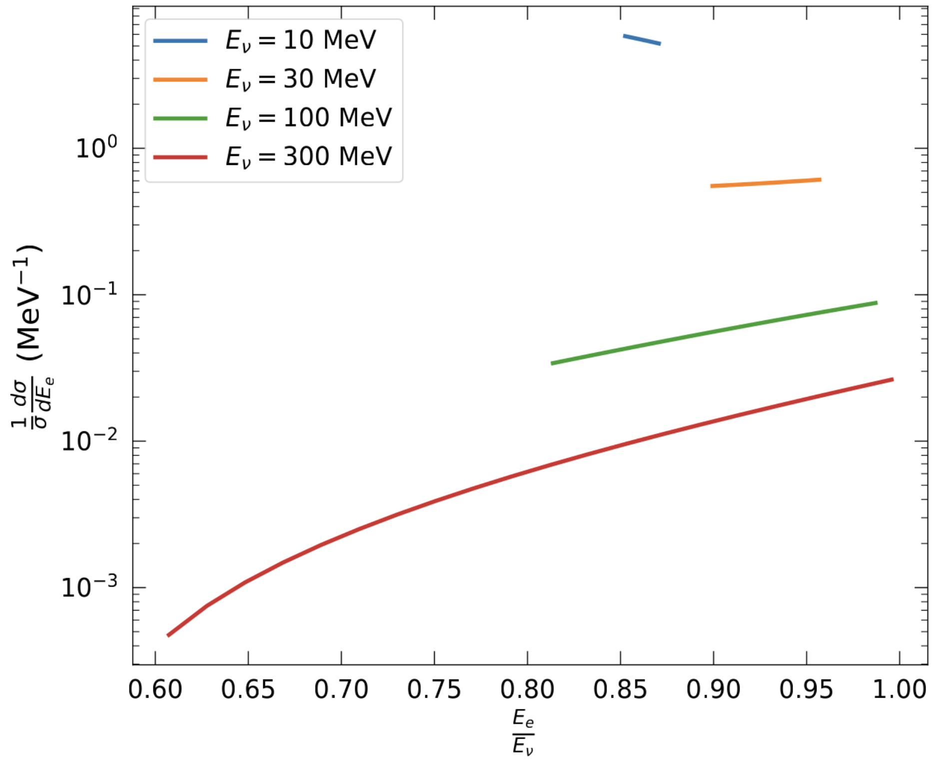
The capture distances increase with higher neutron momentum

Cross Section in IBD

$$\frac{d\sigma}{dt} = \frac{G_F^2 \cos^2\theta_C}{2\pi(s - m_p^2)^2} \, |\mathcal{M}^2|$$

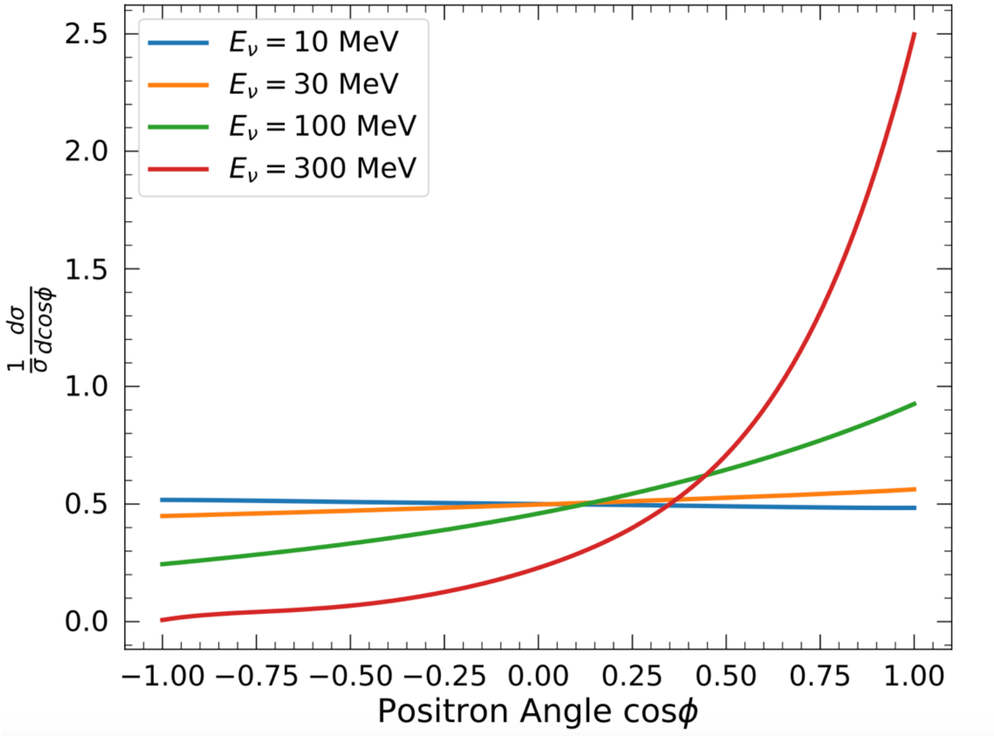
Alessandro Strumia & Francesco Vissani, 2003

- For a given neutrino energy, there is a range of possible positron energies given by the IBD differential cross section
- Favors the lower energy positrons at lower neutrino energies
- For 30 MeV neutrinos, the cross section becomes more uniform
- High energy neutrinos preferentially produce higher energy positrons



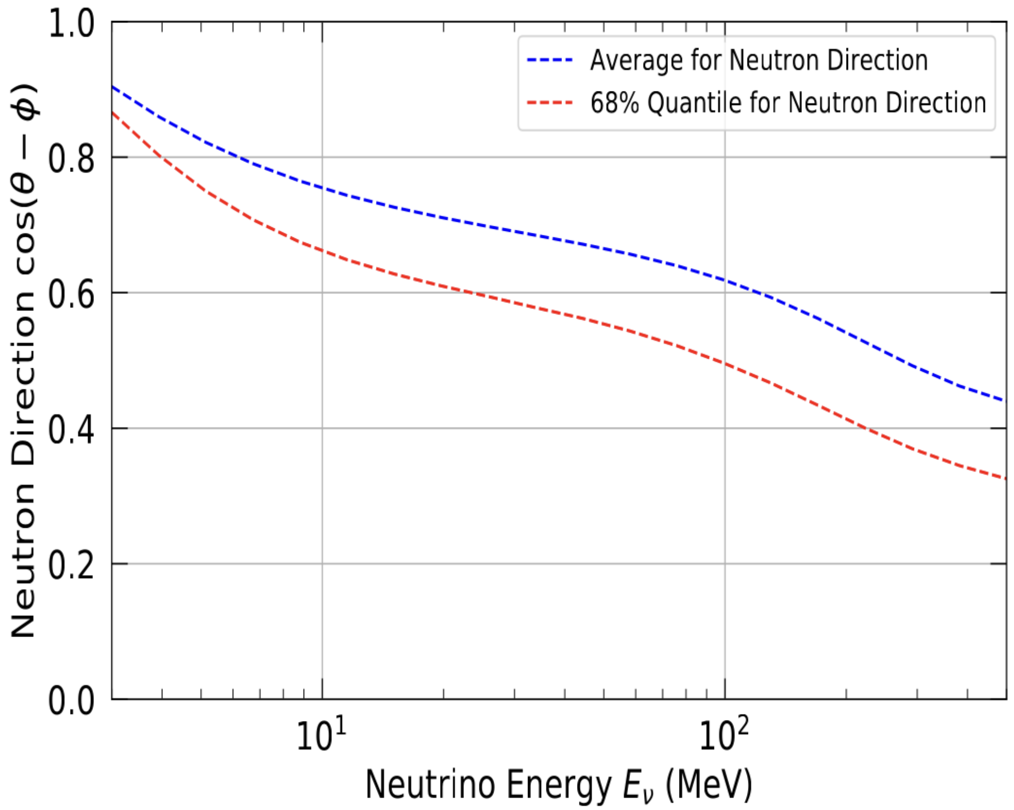
Positron Direction in IBD

- For 10 MeV neutrinos, positrons exhibit a slight backward bias in their emission direction.
- As the neutrino energy increases, the positron angular distribution shifts towards the forward direction.
- The positron direction becomes useful for high-energy neutrinos.



Average Neutrons Emitting Direction in IBD

The inferring the neutron direction is very useful for low-energy neutrinos.



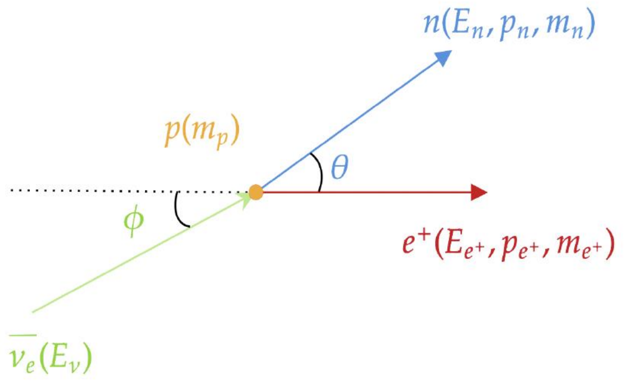
IBD Angular Reconstruction Steps before Diffusion

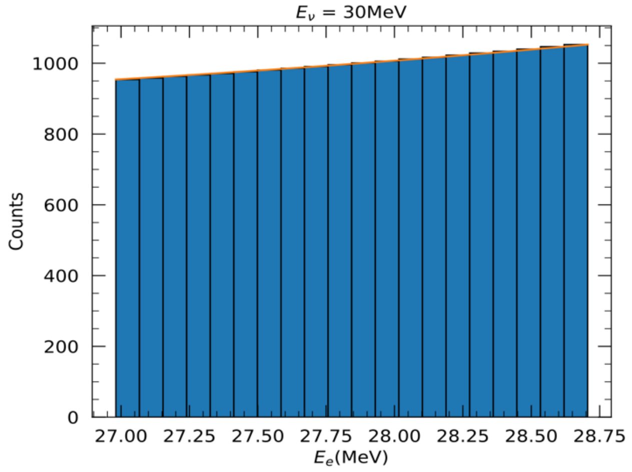
1. Assume a point source with a monochromatic energy distribution

2. 20 evenly spaced positron energies

3. The contribution of the positron energies are weighted by the differential cross section

4. Given neutrino and positron energy, using kinematic to solve everything (2D)





IBD Angular Reconstruction Steps after Diffusion

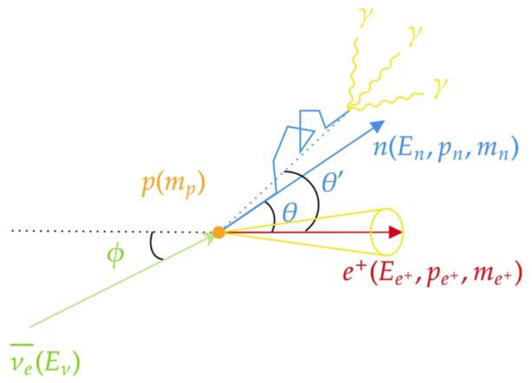
1. Simulate neutron diffusion with momenta value from 1 to 800 MeV at intervals of 1 MeV, each constituting 10000 events

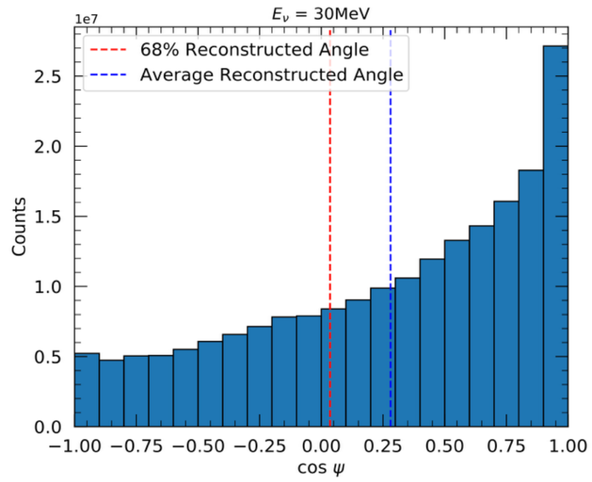
2. Match the corresponding neutron momentum and their diffusion simulations

3. Calculate 10000 neutron capture angles relative to the positron direction

4. Given neutron capture angles and positron energy, using kinematic to reconstruct (3D)

$$\cos\psi = \cos(\phi' - \phi)$$

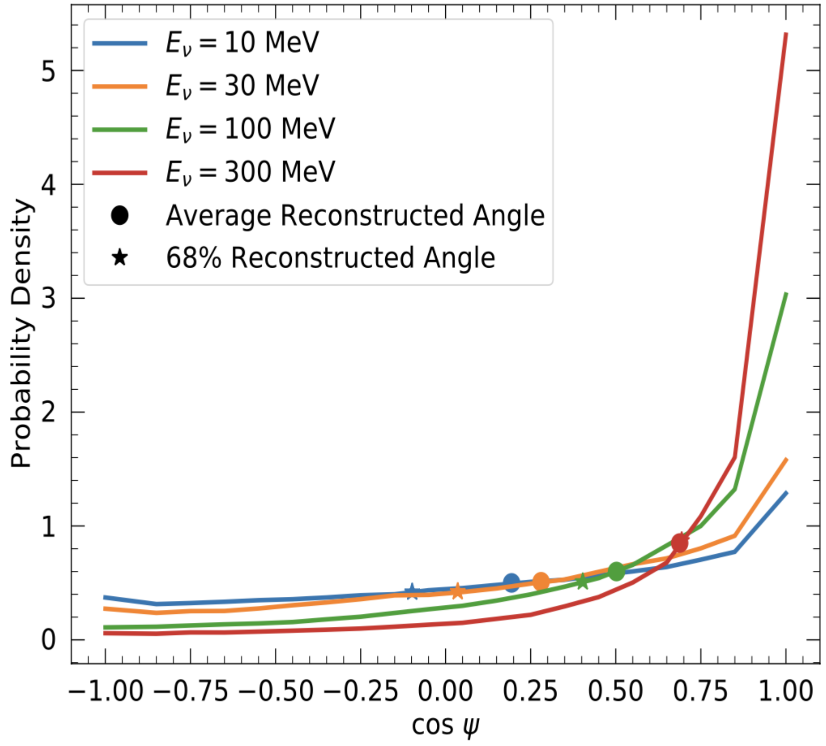




Neutron Capture Information in Improving IBD Angular Resolution

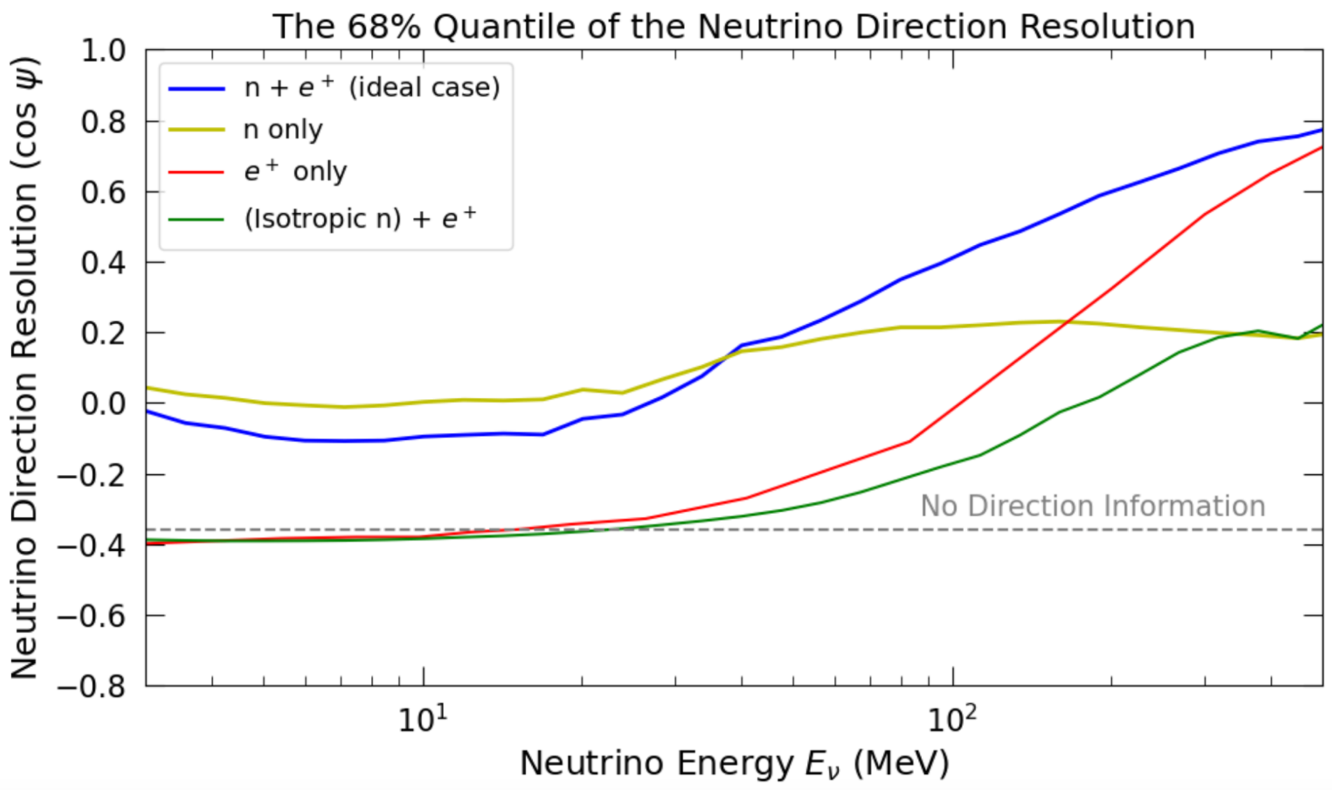
Impossible to reconstruct at the event-by-event level but possible to statistically infer the direction of the neutrinos using multiple events

Neutrino Energy ↑ —> Reconstruction ↑



Neutron Capture Information in Improving IBD Angular Resolution

This method improves the directional resolution for neutrinos in IBD, compared to relying solely on the positron information.



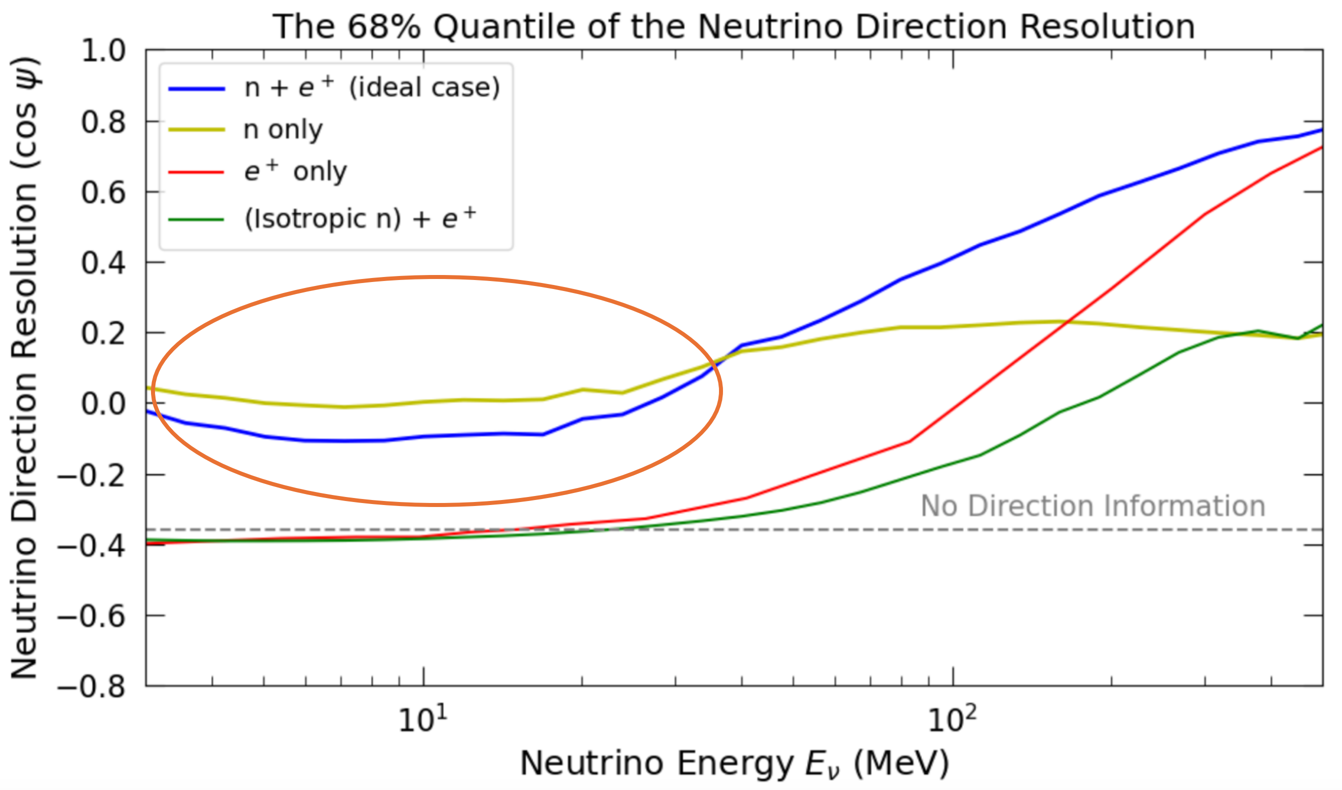
From Liu, Ng in preparation

Neutron Capture Information in Improving IBD Angular Resolution

At low energies, neutron carries most of the directional information.

The isotropic nature of positrons tends to diminish the directional information.

Positrons direction dominates at higher energy.



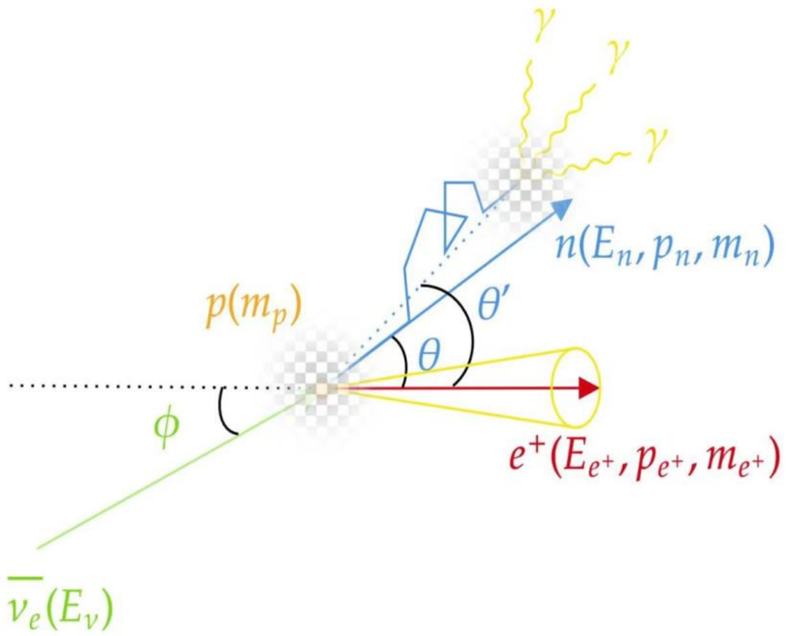
From Liu, Ng in preparation

Vertex Resolution

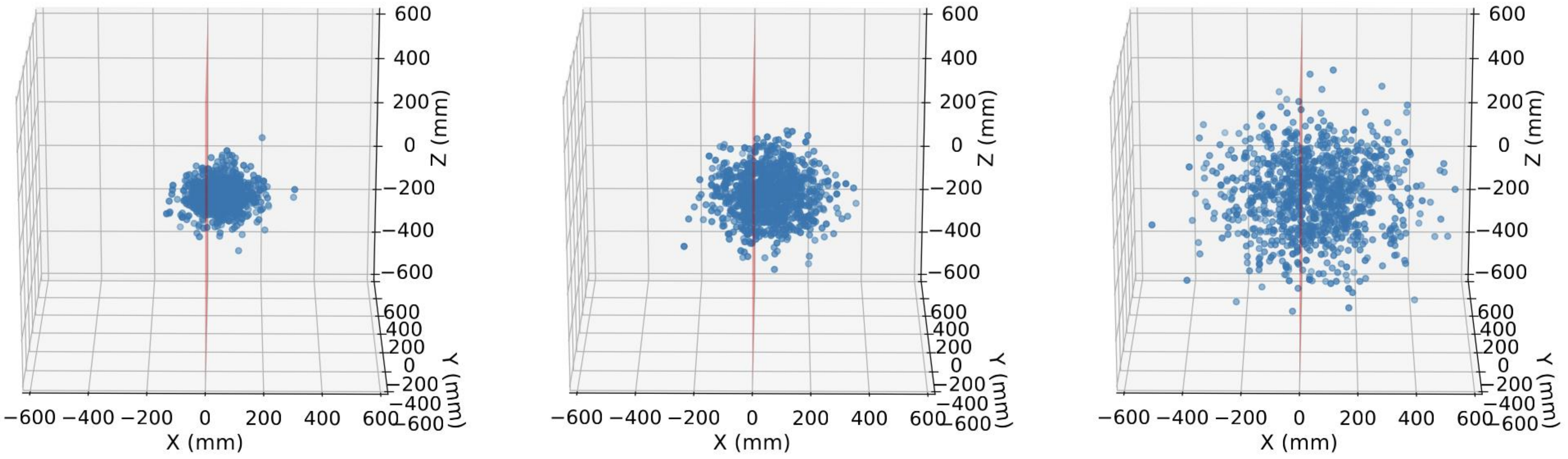
If the vertex resolution >> neutron capture distance —> No neutron direction!

Neutron capture distance ~ 10cm at 50 MeV

Vertex resolution ≳ 30cm



Vertex Resolution



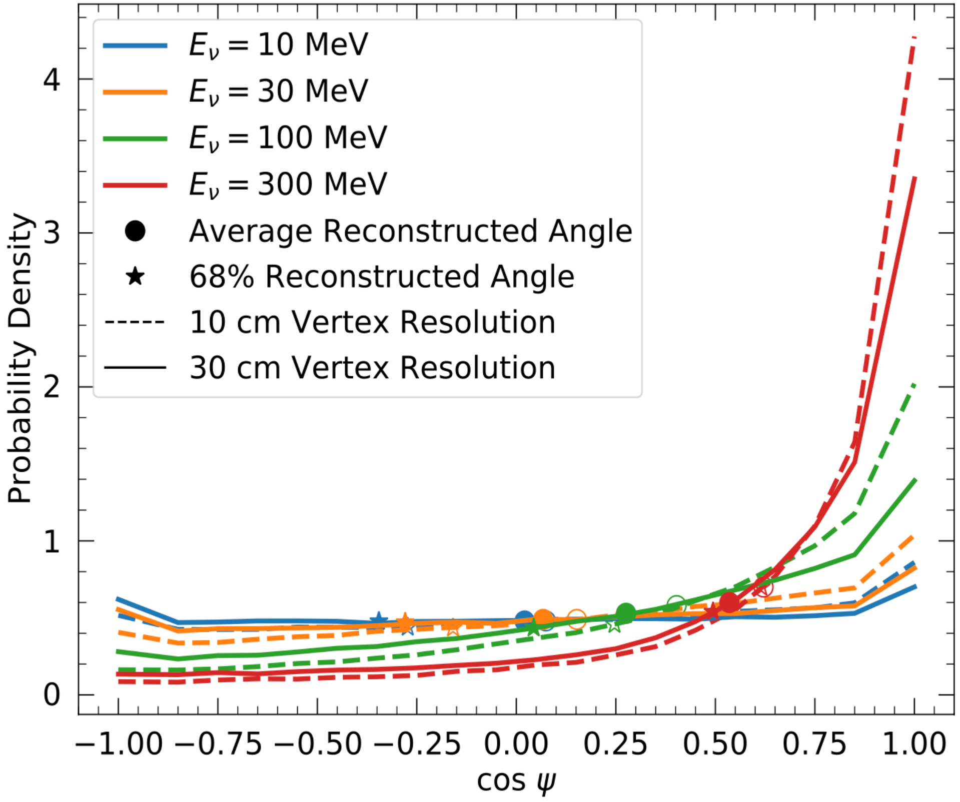
50 MeV momentum neutron capture positions for varying vertex resolution of 0 cm (left), 10 cm (middle) and 20 cm(right)

The neutron capture position retains some information about the original direction, despite the smearing effect of the finite vertex resolution

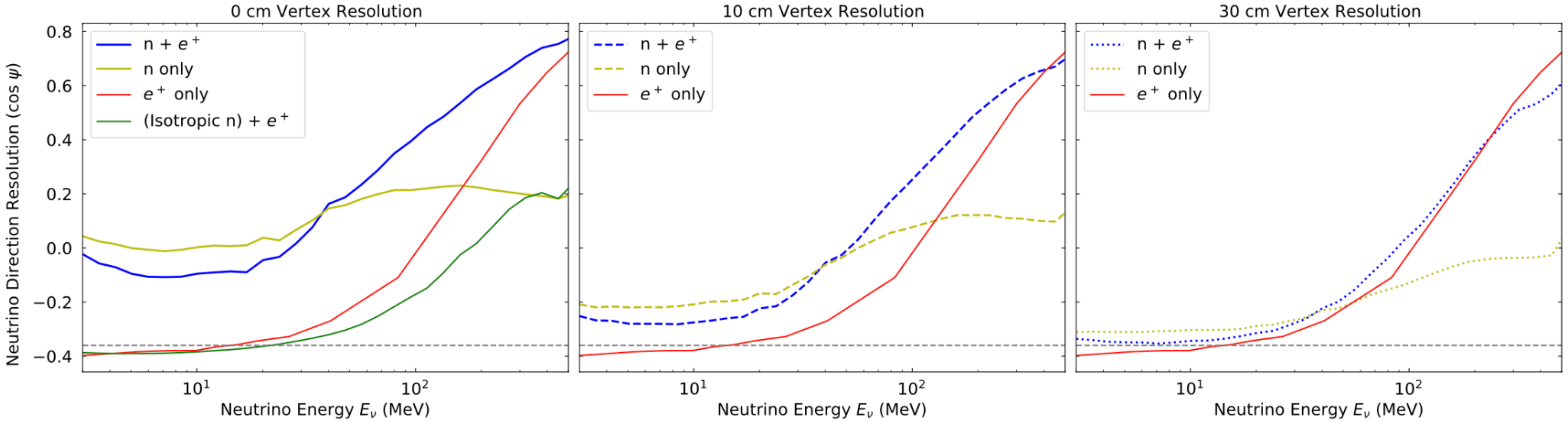
Reconstruction with Experimental Resolutions

Flatter distribution

Reduce the reconstruction resolution



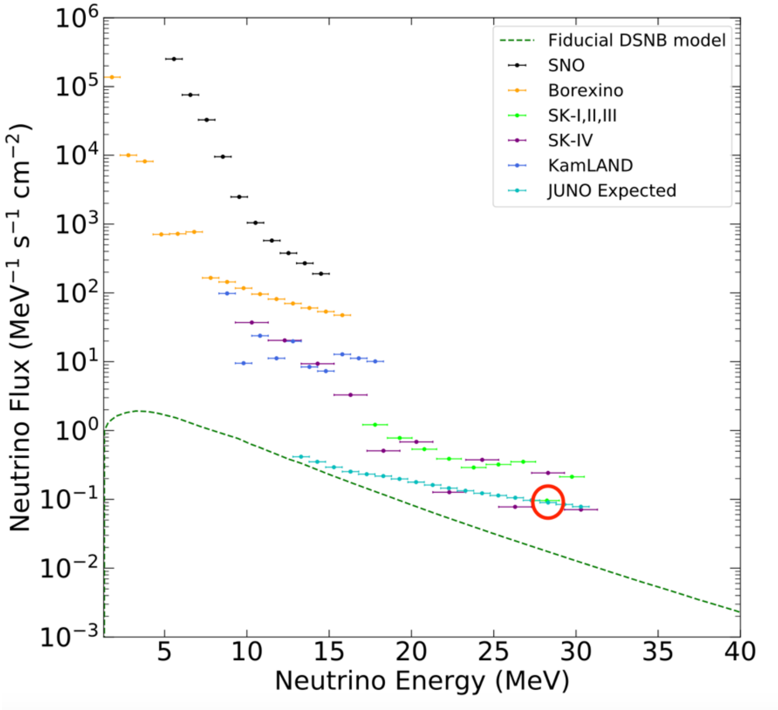
Neutron Capture Information in Improving IBD Angular Resolution



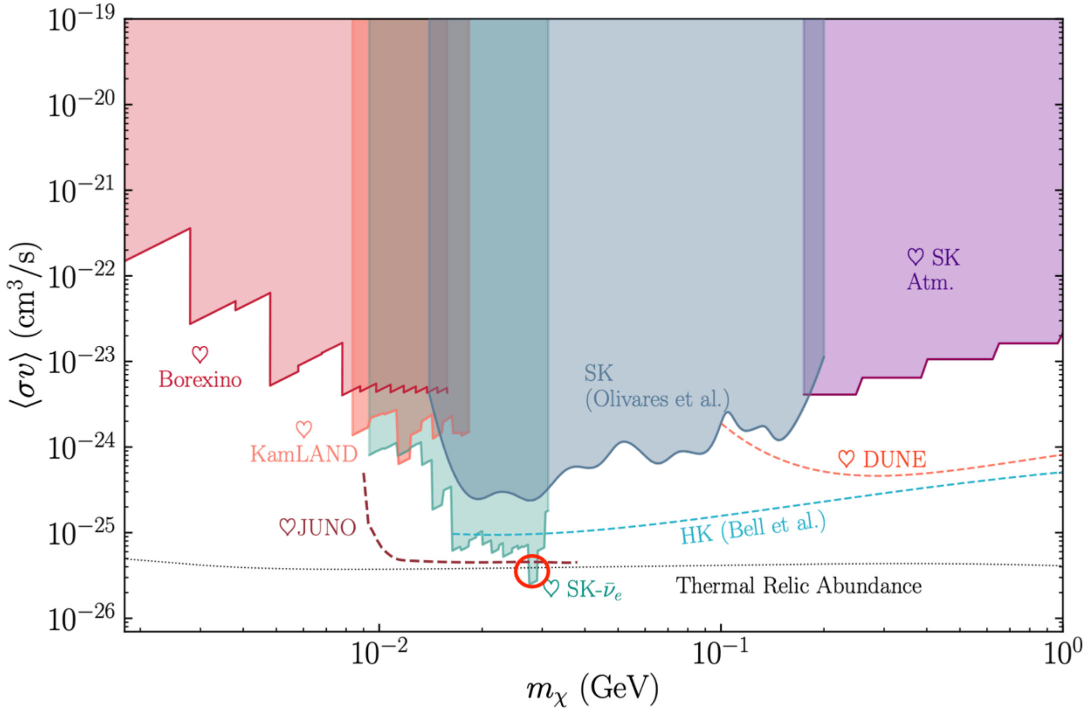
From Liu, Ng in preparation

Vertex resolution ↑ —> Reconstruction ↑

DM Annihilation to Neutrinos



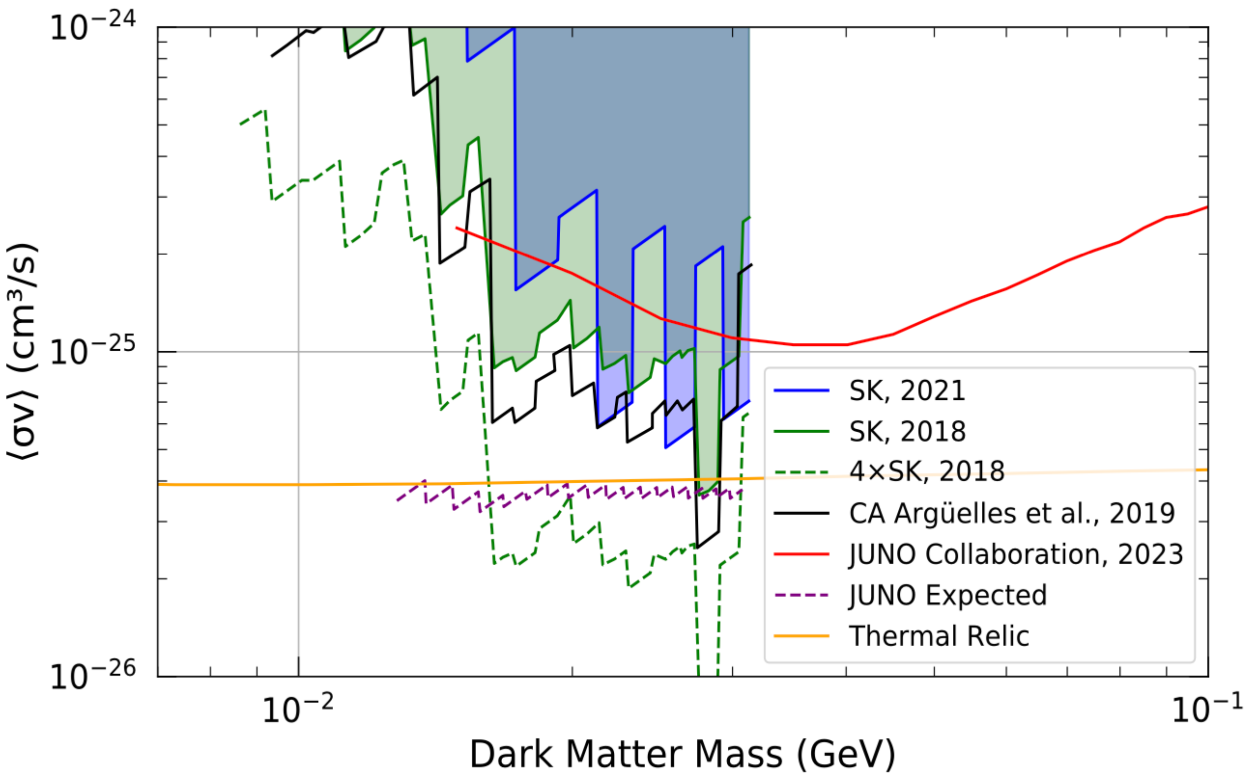
Liu, Ng, 2023



CA Argüelles et al., 2019

The strong constraint is just dominated by one data point

DM Annihilation Cross Section vs Mass



$\chi\bar{\chi} \rightarrow \nu\bar{\nu},\ J_{avg}=5$

$$\frac{\mathrm{d}\phi_{\bar{\nu}_e}}{\mathrm{d}E_{\bar{\nu}_e}} = \frac{1}{2}\langle\sigma v\rangle J_{\mathrm{avg}} \frac{R_\odot \rho_\odot^2}{m_\chi^2} \frac{1}{3} \delta\left(E_\nu - m_\chi\right)$$

Directionality would help us to really touch the Thermal Relic line

Conclusion and Discussion

Neutron capture information could significantly enhance the neutrino directionality statistically.

The ability to recover neutrino directionality depends on the vertex resolution. Our work then motivates the considerations of methods to obtain better vertex information.

This enhanced directional information can be utilized for dark matter searches.

Backup slides

Neutrino Direction

• ν_e + e scattering

1. Good angular information in the water Cherenkov detectors

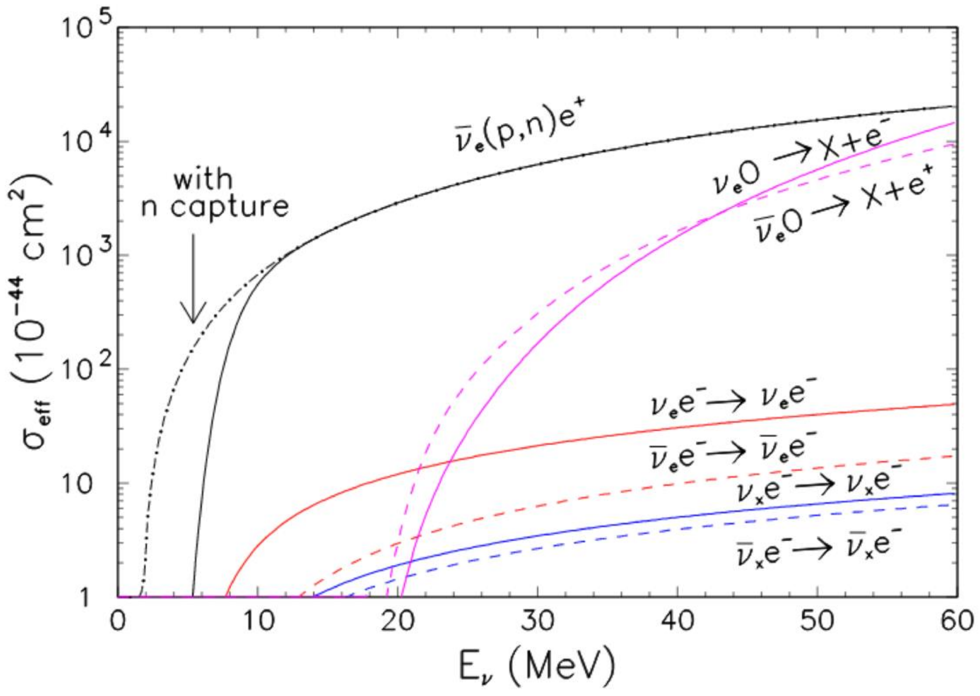
2. Only a minority of the total number of events

• Inverse-Beta-Decay (IBD) $\overline{\nu}_e + \mathrm{p} \rightarrow \mathrm{n} + \mathrm{e}^+$

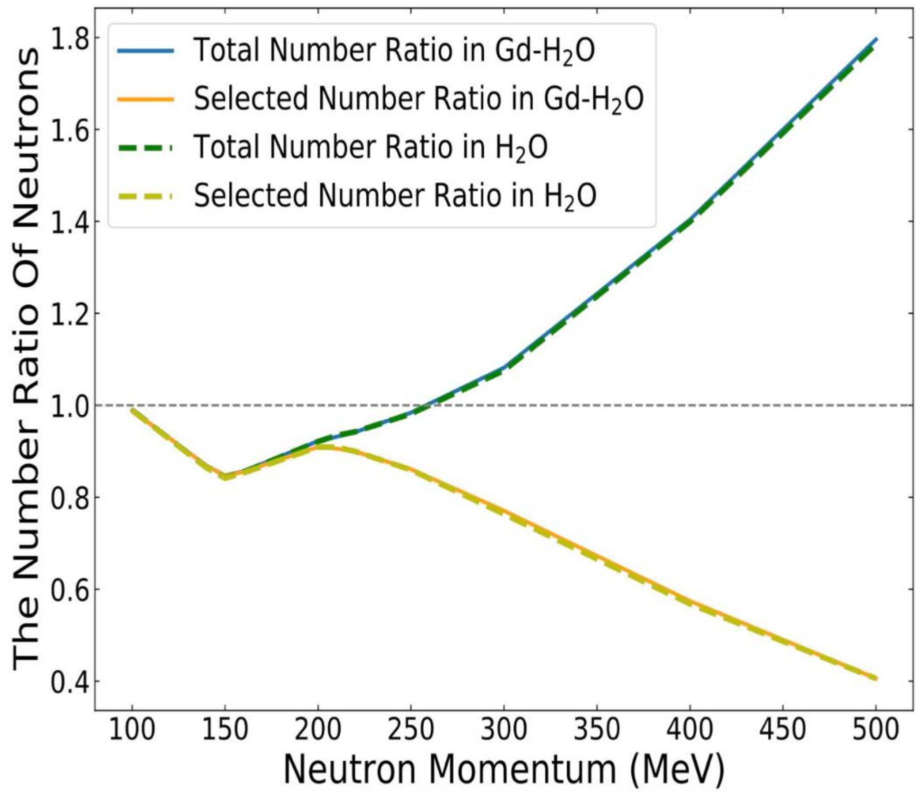
1. A majority of the total number of events (larger cross section)

2. The neutrons has diffusion before capture

3. Only positron angular information before



Single-neutron events selection



The number of neutron capture events per neutron injection event

We focus on single neutron events, which would be easy to identify and analyse experimentally

Positron Angular and Energy Resolution

Positron angular resolution of 10 degrees: adjust the positron direction and consequently alter the neutron capture angle

Consider a constant positron energy resolution of 10%

E_ν \ $\cos\psi$	68% (0°)	68% (10°)
10 MeV	-0.097	-0.10
30 MeV	0.036	0.034
100 MeV	0.40	0.40
300 MeV	0.69	0.68

E_ν \ $\cos\psi$	68% $\cos\psi$(0%)	68% $\cos\psi$(10%)
10 MeV	-0.097	-0.098
30 MeV	0.036	0.036
100 MeV	0.40	0.40
300 MeV	0.69	0.69

Vertex Resolution

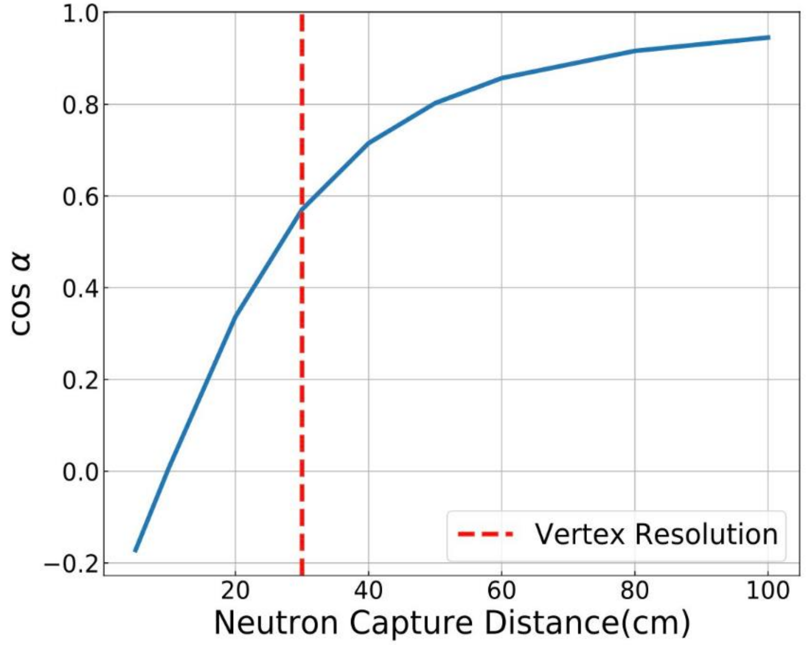


Figure 4.22: The neutron angular resolution as a function of neutron capture distance, with a vertex resolution of 30 cm (red dashed line). The resolution on angle is defined as the 68% quantile of the angle distribution.

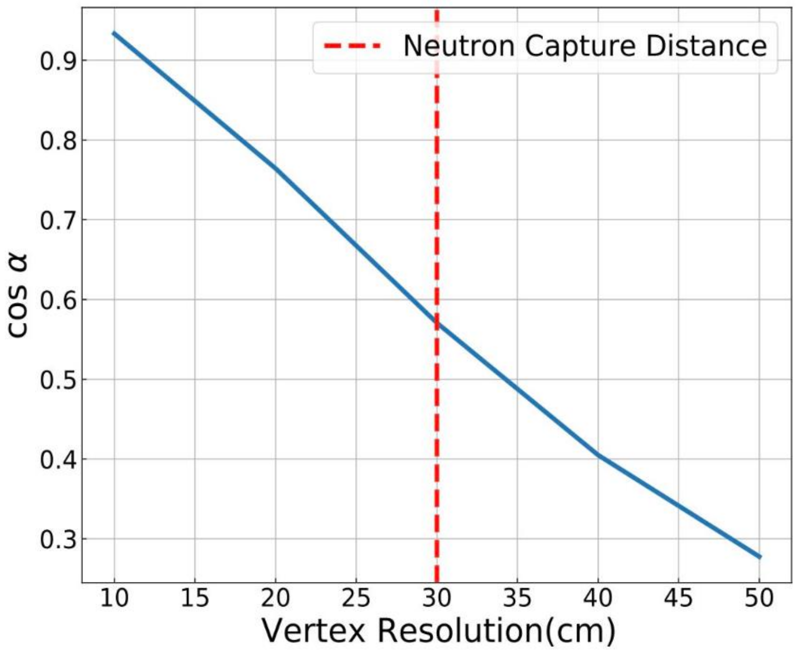
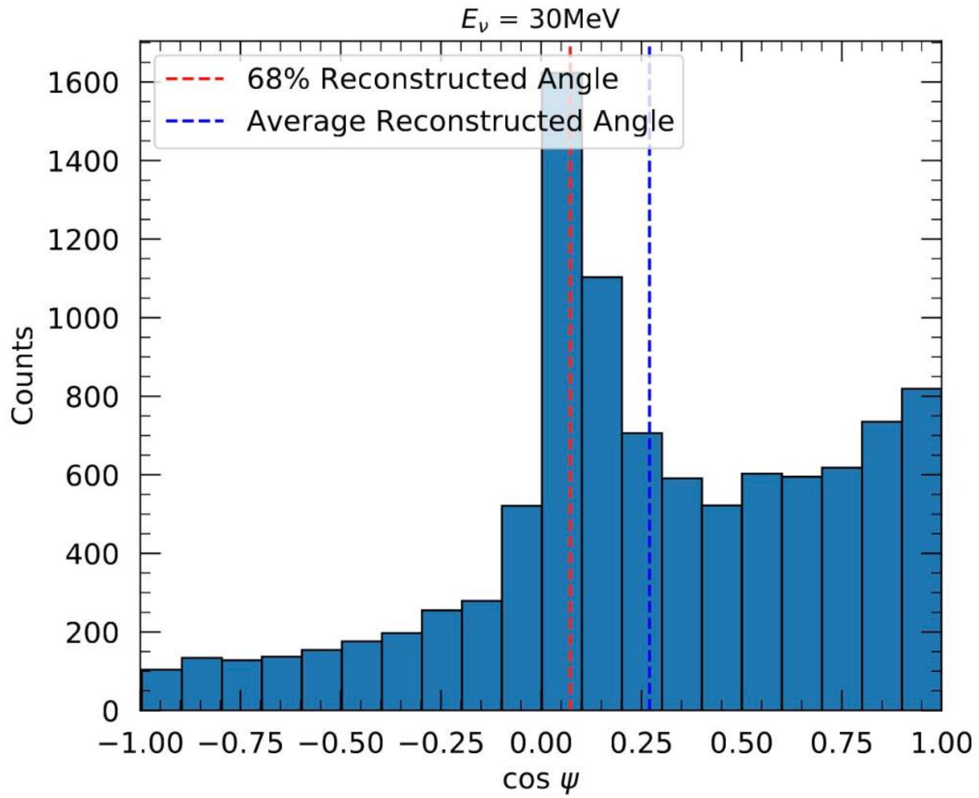
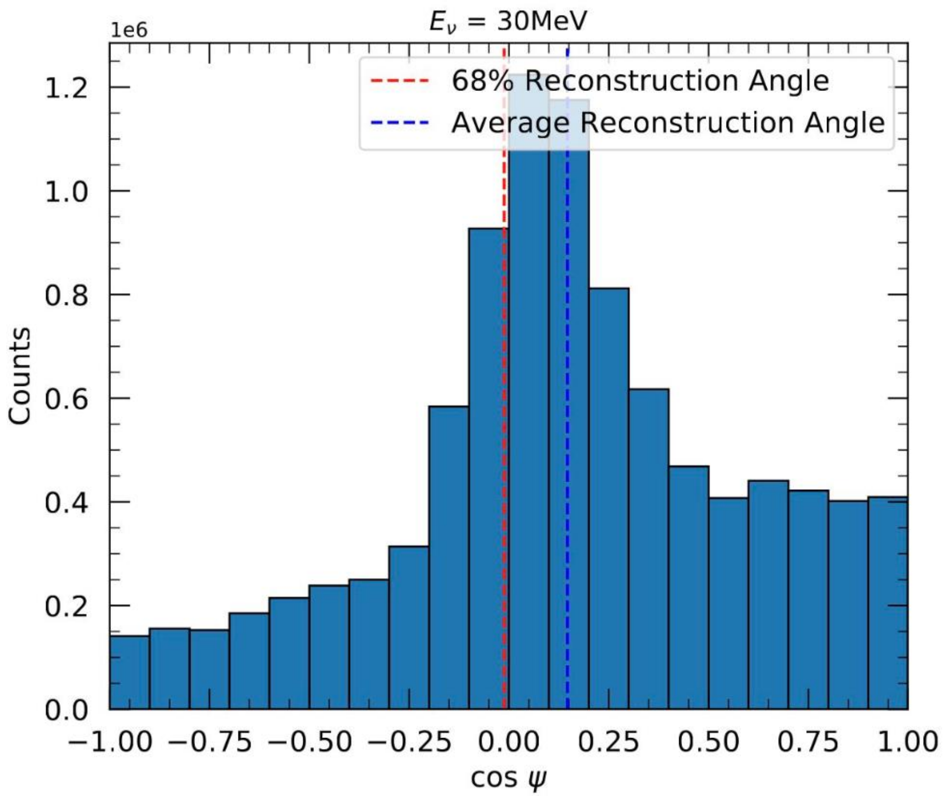


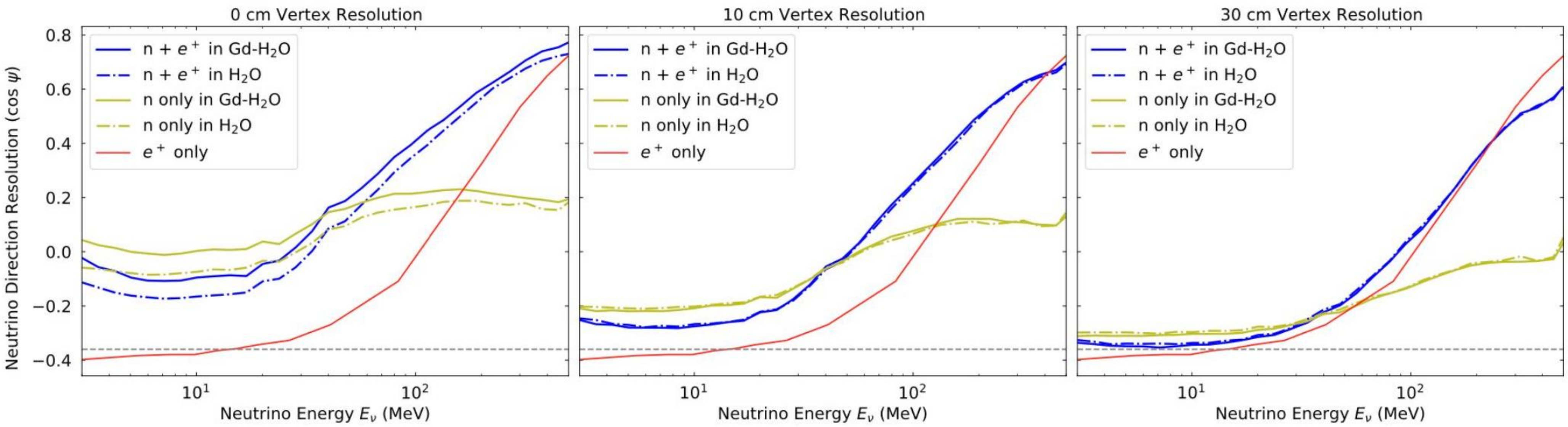
Figure 4.23: The neutron angular resolution as a function of vertex resolution, with a neutron capture distance of 30 cm (red dashed line). The resolution on angle is defined as the 68% quantile of the angle distribution.

The reconstruction with average positron energy



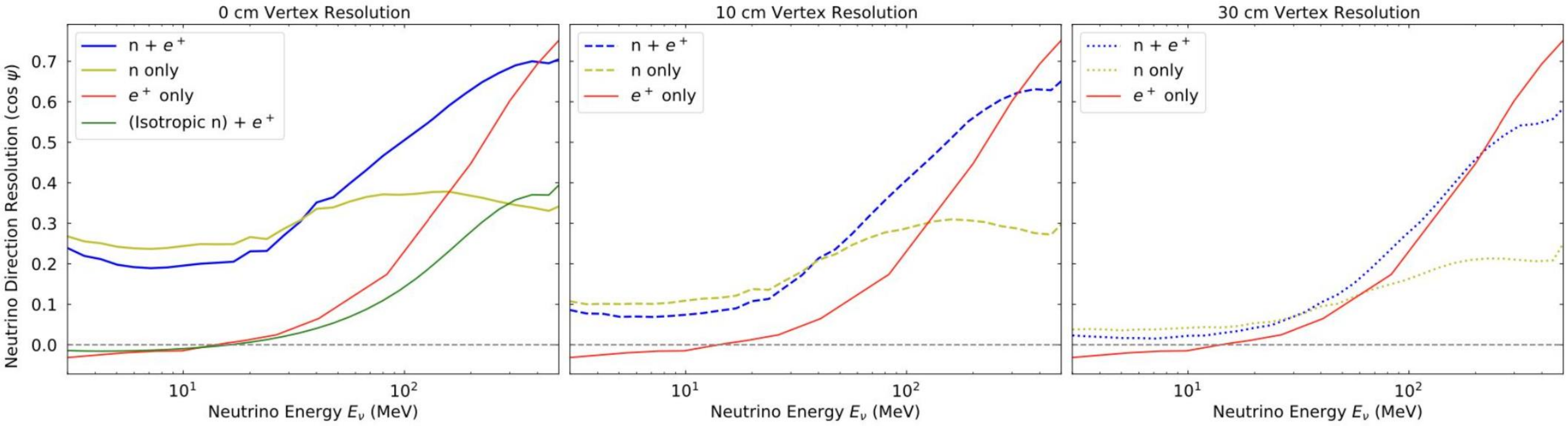


Reconstruction in Gd-loaded Water and Pure Water



From Liu, Ng in preparation

The average value of the reconstruction resolution



From Liu, Ng in preparation